Metal Matrix Composite Brakes Using Titanium Diboride

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Project ID mat142

Overview

Timeline

- Project Start Date: Sept 2017
- Project End Date: Sept 2019
  - 65% Complete

Budget

- Total project funding
  - DOE - $300k
  - Arconic $360.8k (in-kind)
- 45/55 Cost Share with Arconic
- Funding Received: FY17 $300k

Barriers

- Barriers to more widespread use of MMCs for vehicle lightweighting are:
  - the costs of the feedstock, especially the insoluble reinforcement (particle, whisker, or fiber)
  - the cost of combining the reinforcement with the matrix in production
  - the cost of shaping / machining MMC components.

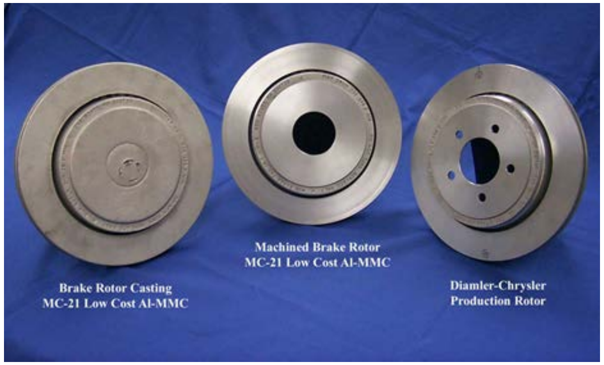
Partners

- LightMat CRADA Partner: Arconic

Relevance

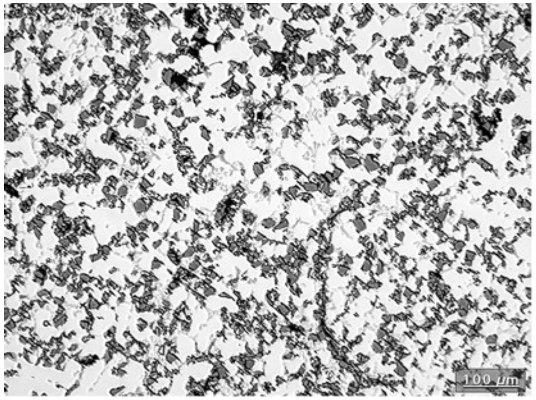
Objective

- Reduce the weight of brake rotors by >50% over the current cast iron materials
- Improve brake performance, wear life, and life cycle cost over cast iron systems
- Develop an Aluminum MMC material that shows appropriate wear resistance and tribologic properties
- Show the potential for a cost / benefit ratio appropriate for commercial development



Impact

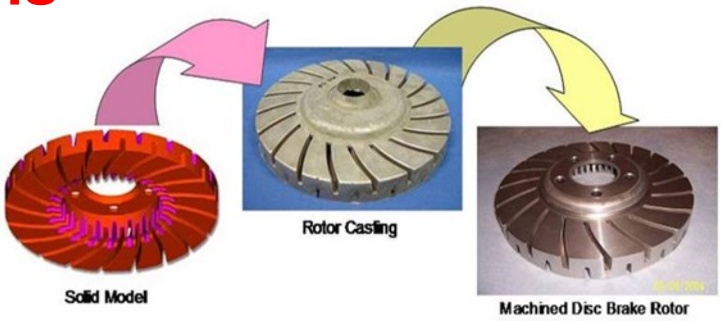
- A 50% weight saving in the rotor has been calculated to correspond to an improvement in fuel economy of 0.25 mpg due to weight reduction and lower rotational inertial energy losses (This number can be much higher in vocational vehicles)
- Aluminum MMC rotors may show significant life cycle cost saving and environmental benefit from reduced wear rate



Relevance

Drivers for Change in Braking Systems

- Aluminum MMCs can provide combinations of high friction coefficient, particular heat transfer characteristics and increased wear life that can **favorably affect system life cycle cost.**
- A 50% increase in wear life can double the interval between rotor change-outs and can affect the economics for those vehicle sensitive to down time



- A 50% savings in mass in a rotating and unsprung location can lead to a **0.25 to 0.35 mpg fuel saving** in a mid-sized car, potentially higher in high duty cycle –buses or city driving
- **Environmental Concerns-** “Wear particles from cast iron brakes are the second largest source of particulate emissions from a vehicle. In urban areas, around 55% of total non-exhaust PM10 (particulate matter smaller than 10 micrometers) emissions is from brake wear.” *

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*** https://thebrakereport.com/is-now-the-time-for-lightweight-brakes/**

Relevance

Why change now?

The landscape has changed in the last 10 years

- Energy harvesting in electric/hybrid vehicle operation decreases the amount of energy that must be dissipated by the mechanical brakes by as much as 40%
  - Energy harvesting can allow for much lower front brake temperatures, enabling the use of lighter weight, lower melting temperature alloys as rotors
- Cast Iron rusts and rusty surfaces are hard to manage in brake-by-wire systems that are tasked with balancing mechanical brake force with energy harvesting
  - Consumers demand a smooth stop (Driver feel and NVH issue).
  - Corrosion resistant and low wear alloys (aluminum MMCs) may provide better control.
- The next generation of vehicle may need drastically improved durability and longer maintenance intervals if they are to be used in new mobility strategies (ride share, fleet ownership, etc.)
  - **TiB_2 reinforcement** offers an opportunity to improve wear resistance at a lower particle loading because of improved ceramic – aluminum bonding
- SiC reinforcement is costly when prepared for inclusion in an aluminum composite (Particle size fraction constraints, SiO_2 coating, etc.). **TiB_2 has much improved wetting** with aluminum allowing for finer particle size, better homogeneity and may prove to be lower cost overall due to lower particle loading required and reduced compositing time for the same friction and wear performance.

Approach

Cast TiB_2 reinforced aluminum brake rotors in several different reinforcement loadings and test for friction and wear performance

Task 1 - Raw Material Production

Arconic Technology Center (ATC) will produce 70kg-50 volume percent Al-TiB2 master alloy and 150kg A356 casting alloy to PNNL.

Task 2 - Casting of MMC Plate

PNNL will use the Al-TiB2 master alloy along with the A356 aluminum to cast 4 MMC billets of MMC composition (5, 10, 15, 20 vol% TiB2) utilizing PNNL MMC casting technology. Effort will develop high speed compositing techniques to mix TiB2 particulate into the aluminum matrix to address cost barriers associated multistep Al-SiC MMC casting processes in current practice

Task 3 - Machining MMC Test Rotors

PNNL will take the MMC plate and machine 4 rotors of each composition. The cast rotors will be machined to subscale rotor configuration and tested on an instrumented brake dynamometer at PNNL for friction characteristics (friction coefficient and wear rate) using several different pad compositions.

Task 4 - Material Characterization

Optical microscopy will be used to characterize the materials for composition, particle homogeneity and porosity levels

Complete

Task 5 - Brake Wear Testing

PNNL, utilizing the dynamometer, will run industry standard wear tests on the four produced MMC rotors. Post test characterization will be done to analyze wear track and transfer layer chemistry.

Approach

Task Number & Brief Description	FY17				FY18				FY19			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1: Raw Material Production **(Arconic Task)**												
Task 2: Casting of MMC Billet												
Task 3: Machining of MMC Test Rotors												
Task 4: Material Characterization **(Arconic Task)**												
Task 5: Brake Wear Testing												
Task 6: Final Report												

Milestone 1: Casting trials completed with rotor castings of each TiB2 loading level ready for machining into rotor test disks - 2nd Qtr FY18 – **Completed**

Milestone 2: Complete wear testing of at least one pad material paired with each of the TiB2 loading levels – 2nd Qtr FY19 – In Progress

Deliverable:

Final Report describing project results including wear and friction performance and material characterization.

Accomplishments

- Task 1 Raw Material (pressure infiltrate master alloy) production is complete (reported last year)
- Task 2 - Casting of MMC Plate
  - Mixing trials began in August 2018
  - Trials involve melting A356 with appropriate amounts of 60% reinforced TiB2-Al master alloy in PNNL stir casting machine.
  - Graphite impellers of three different designs were used however the star design below produced the best particle mixing during the limited casting trials
  - Used the star impeller for all mixing, except 15 vol% plate. 15 vol% plate used an impeller which had staggered vertical blades, but half the thickness profile (normal to fluid).

Graphite impellers

Star design mixing impeller

Accomplishments

Task 2 - Casting of MMC Plate

- Completed 5, 10 and 15 vol% cast TiB2 plates.
- Casting parameters were varied to achieve smooth pours (homogeneous particle distribution). Final stir casting parameters were:
  - For 5 and 10 vol% composites, blocks of 356 and master alloy were heated for 4 hrs at 780C to melting, then the impeller was lowered to near the crucible bottom and the melt was stirred at 500 RPM for 1 hour.
  - For the 15 vol% composite the schedule above was followed except that the mixture was stirred at various RPM for 1 hour to break particle rich clumps, then stirred for another 1 hour at 500 RPM.
- Melt was then gravity cast into steel book molds to cast plates roughly 8” x 12” x 1” thick.

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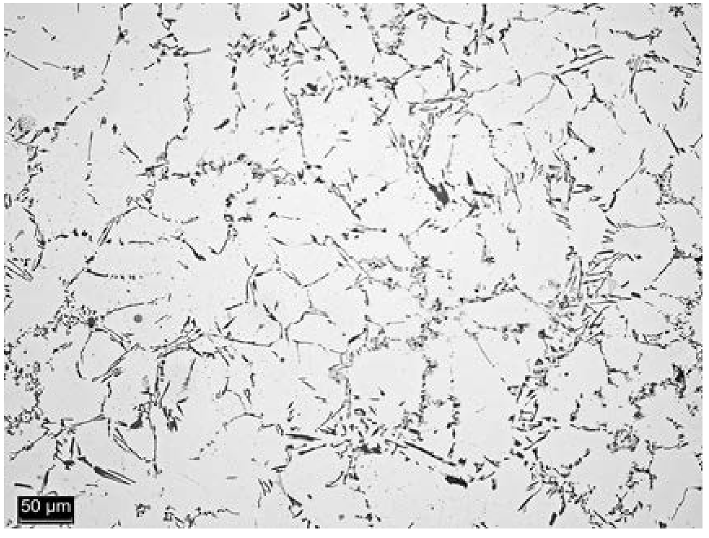
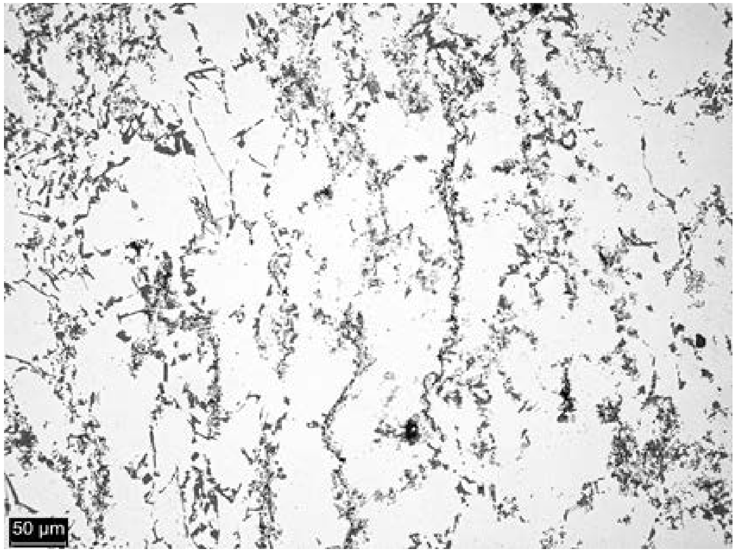
Accomplishments

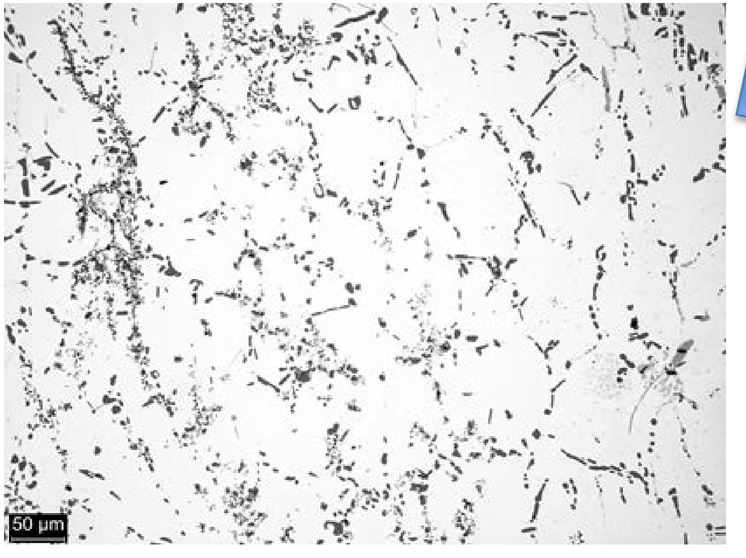
Some porosity was observed.
Expected in gravity casting in thin book molds with high solidification rate.



As-Cast 5 vol % TiB2 reinforced A356

Hot rolled @480C - 30% reduction





Heat treated to T7
 (8-hrs @ 540 C, with water/glycol quench (simulate hot water quench) below 230 C, followed by 8-hrs @ 225 C)

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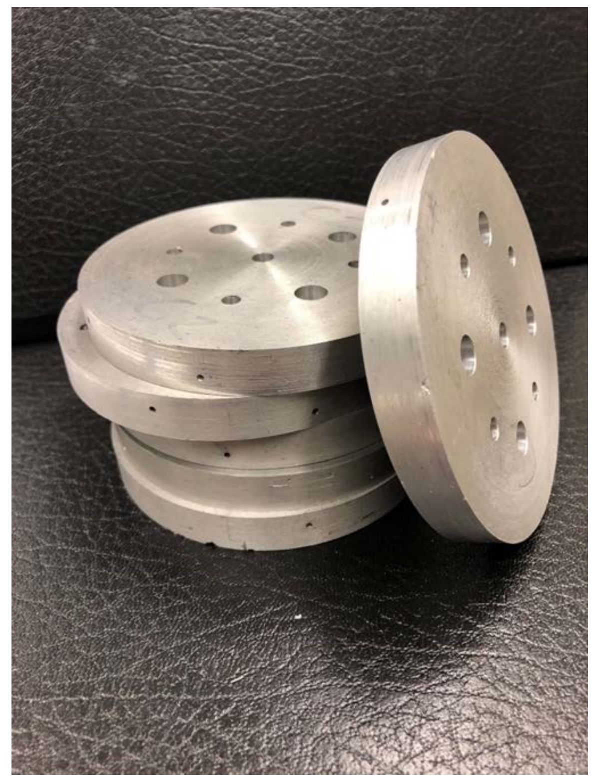
Accomplishments

- 3 to 4 rotors cut from each book mold
- 100 mm dia. x 12.5 mm discs have been machined from the 5, 10 ,and 15 vol% plates



Collaboration and Coordination with Other Institutions / Future Research

- The tasks below illustrate the breakdown of the collaborative work load

PNNL Task — Arconic Task — Jointly Executed Task

Resources: LightMAT (Pacific Northwest National Labs): MC21 MMC Stir Casting Equipment, Machining and Grinding Capabilities, Brake rotor/pad friction pair wear testing equipment (custom Brake Dynamometer Testing Equipment)

- **Task 1 - Raw Material Production**
  - **Arconic Technology Center (ATC) will produce 70kg-50 volume percent Al-TiB2 master alloy. ATC will provide a 150kg A356 casting alloy to PNNL. ATC will also do initial material characterization. - Jim McMillen (ATC Resource)**
- **Task 2 - Casting of MMC Plate**
  - **PNNL will use the Al-TiB2 master alloy along with the A356 aluminum to cast 4 MMC billets of MMC composition (5, 10, 15, 20 vol% TiB2) utilizing PNNL MMC casting technology. - Glenn Grant (PNNL Resource)**
- **Task 3 - Machining MMC Test Rotors**
  - **PNNL will take the MMC plate and machine 4 rotors of each composition to dynamometer test specifications. Samples of the material after machining will be supplied to ATC for characterization.**
- **Task 4 - Material Characterization**
  - **ATC will characterize the materials for composition and mechanical properties using Arconic equipment and machined chips from the MMC rotor production. - Jim McMillen (Lead ATC Resource)**
- **Task 5 - Brake Wear Testing**
  - **PNNL, utilizing the dynamometer, will run industry standard wear tests on the four produced MMC rotors. - Glenn Grant (PNNL Resource)**
- **Task 6 - Compilation of Results (Final Report)**
  - **ATC and PNNL will compile a final report of findings. Jim McMillen (Lead ATC Resource)**

Future Research

Any proposed future work is subject to change based on funding levels

Responses to Previous Year Reviewer Comments

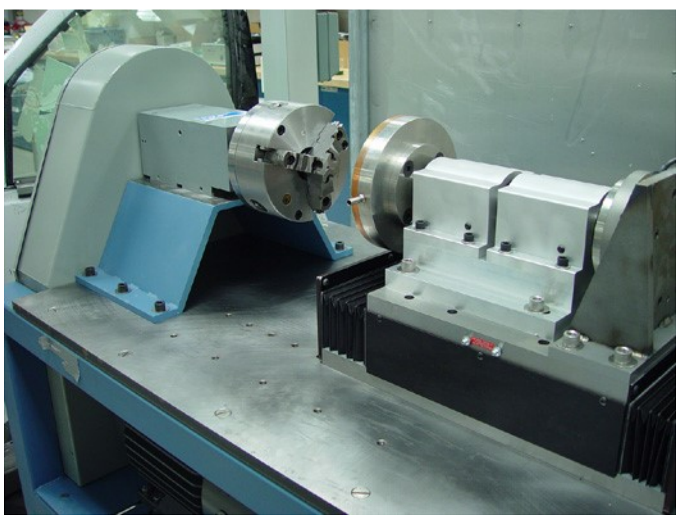
- ….no information on the TiB2 MMC manufacturing process, and there was no discussion about the challenges of getting the desired composition and manufacturing process for optimum brake material manufacture.
  - We have included some more information about our compositing process in this report, however the methodology we used here to incorporate the insoluble particles is probably not the method that will be considered in production. We are using stir casting to mix 60% reinforced master alloy with 356 and then conventional gravity casting, neither optimal nor the likely casting process for a production methodology. Based on microscopy and measurement of area fractions, we have been able to reach targeted reinforcement levels of 5,10 and 15% reinforcement, but gravity casting leaves some porosity issues that would not occur in the production casting process. The likely process (and the one that was successful at producing low porosity MMC rotors in the mid 2000s) was a system that introduces powder below the melt surface at the impeller, then used, instead of gravity casting, a pressure or squeeze cast process to cast the rotor closer to net shape. This process in the past produced good MMC homogeneity and casting throughput.

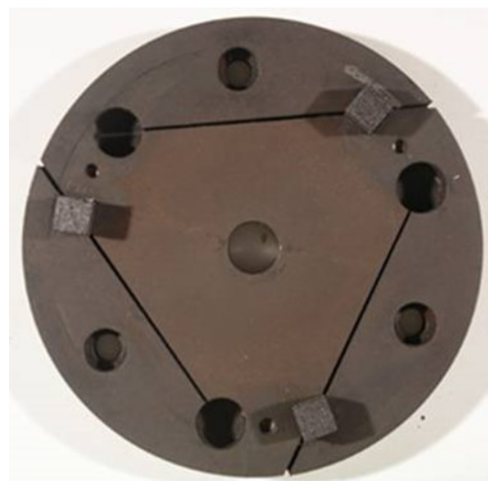
- There are no cost analyses and no unit cost for the TiB2 brake discs
  - The project is primarily focused on a demonstration that a TiB2 reinforced aluminum rotor can achieve appropriate friction coefficients and enhanced wear performance over baseline cast iron and as compared to a large body of previous project data on Aluminum SiC composites. Arconic is also interested to see if their low cost TiB2 materials can affect the raw material cost component of the overall MMC cost.
  - The cost advantage over cast iron will be realized in the long term durability, reduction in repair/replacement interval and a reduction in the out-of-service time (for high duty cycle vehicles, ride share, vocational heavy duty vehicles, buses etc.). If it is found that the TiB2 composite shows reasonable performance in wear and friction coefficient then a more directed effort to establish a production process and a cost analysis will be undertaken

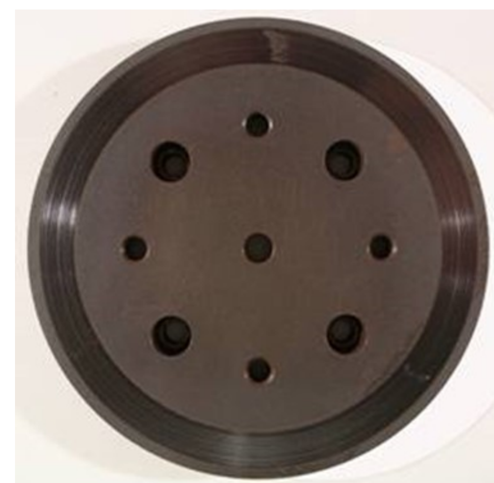
Proposed Future Research
Evaluation of Friction Pairs - Subscale testing

- Friction Pair Testing
  - 10 cm diameter rotor disks
  - Test run at constant torque for fixed time
  - Rotor temperatures measured by thermocouple 2-5 mm below friction surface
  - Temp maintained by cooled backing plate

- Three 0.5 x 0.5 x 1 cm pads are mounted to gimbaled holder and rotated against the pads
- Axial loads required to maintain torque are measured
- Friction coefficients are then calculated and post test weights are used to calculate wear rate







Wear tester at PNNL

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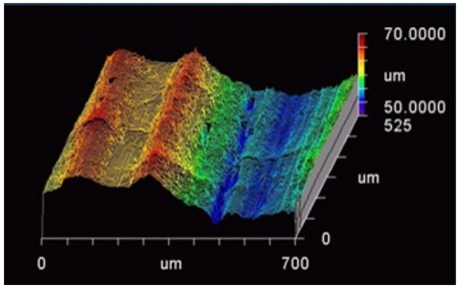
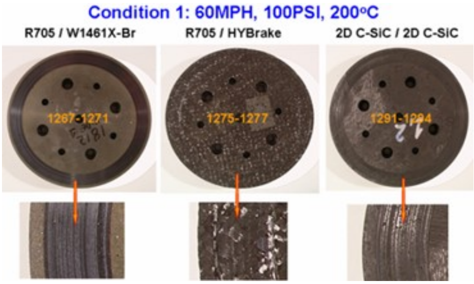
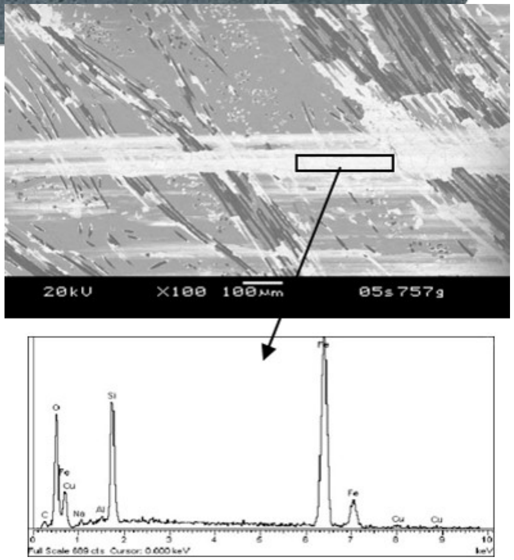
Proposed Future Research
Tribology Characterization

- Tribologic characterization helps to define appropriate friction pairs
- The development of a stable transfer layer is key to stable friction coefficients

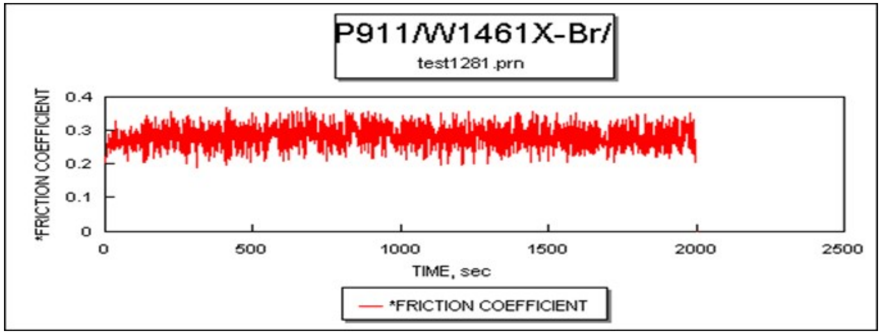




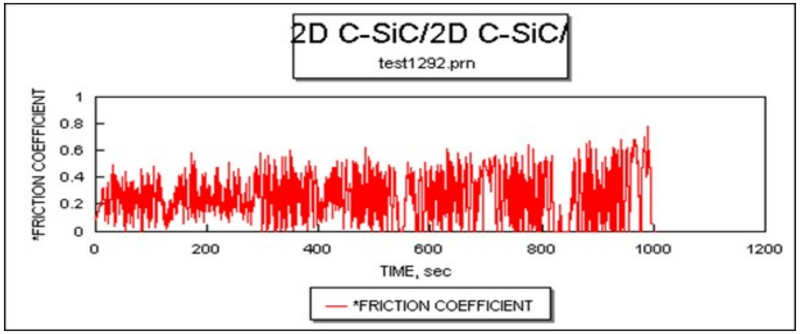
Typical wear tracks for cermets and C/SiC rotor materials



SEM EDX analysis of transfer layer



When appropriate friction pairs are used, stable friction coefficients result



When the pair is not optimized the system is unstable

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Summary

Why a LightMat Project?

- Technology / Commercial opportunities have changed in the last decade offering an opportunity to re-evaluate Al-MMC brake rotors.
- The Pacific Northwest National Lab has test equipment, expertise and a large historical database on SiC (and other) based MMC brake performance from previous projects, which can be compared to Arconic's new TiB_2 reinforcement concepts.
- Baseline performance data developed in this project will allow Arconic to evaluate the viability of a new Al-MMC concept, and move towards commercialization in a lower risk environment.

Approach

- This project will investigate using Titanium Diboride (TiB_2) as a substitute for the more traditional MMC efforts with Silicon Carbide (SiC) in an effort to improve automotive brake performance, wear life, and reduce cost.

Impact

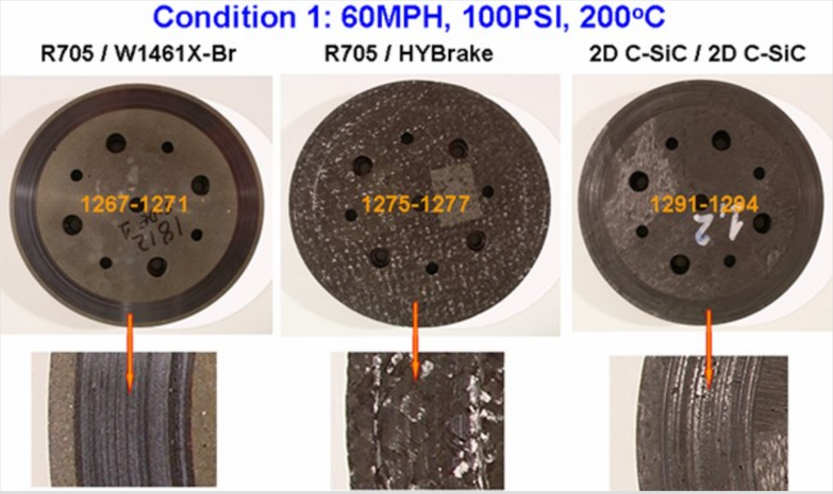
- A 50% weight saving in the rotor has been calculated to correspond to an improvement in fuel economy of 0.25 mpg to 0.35 mpg due to weight reduction and lower rotational inertial energy losses
- Al MMC rotors, using TiB_2 have the potential to show lower overall fabrication and life cycle cost and better performance in wear and wear particulate emission over current cast iron.

Technical Backup Slides

Evaluation of Friction Pairs Test Conditions

- Typical Vehicle Operating Conditions
  - On-highway (mostly snubs, with occasional stops)
    - moderate to high speeds
    - low brake pressures - low brake temperatures
  - City driving (frequent stops and starts)
    - low to moderate speeds
    - low to moderate brake pressures - high brake temperatures
  - Mountain descents (long brake applications)
    - low to moderate speeds
    - moderate to high brake pressures - high brake temperatures

These considerations led to two test conditions



Previous work - Dyno Testing Results of Alum SiC MMC rotors

Test Description		Testing Source	Pass (P), Nonconforming (N)	Remarks / Reaction Plan for Nonconforming Items
Dyno Simulation of AMS &Fade test.		Link Engineering	Pass(P)	AMS results are promising .
Dyno Simulation Of Laurel Mountain Hot Roughness Brake test-		Link Engineering	Pass(P)	Rotor passes the test. Need to increase Brake Caliper roll back space to compensate thermal expansion of Rotor prevent scoring.
Dyno lining Wear Vs Temperature		Link Engineering	Pass(P)	Need to develop new lining for ALMMC, this Akebono lining is decomposing faster at 300C or higher temperatures.
Env. Dyno Brake Noise Test (w/steady drag)		Link Engineering	Pass (P),	Need to develop new lining for ALMMC, this Akebono lining is at the border line of Noise Index, rating is Yellow.
Disc Wear w/Low Pressure Drag		Link Engineering	Pass (P)	Disc wear loss for MC21 is negligible. Recommendation is use only MC21 or 20% or higher SiC.
Dyno Brake Effective Test		Link Engineering	Pass(P)	Results are promising, however in temperature sensitivity cycle temperature reaches to above 500 deg Celsius because Link did not stop the test at 400 deg C. parts survived 500 deg C test.